Colliding Laser Produced Plasma experiments on Carbon group elements

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Abstract

The study of the behaviour of Sn plasmas produced by laser ablation has been relevant to source development for lithography at 13.5 nm [1]. The work presented here is primarily concerned with the difference in plasma velocities for laser produced plasmas of group 4 elements from carbon to lead, with emphasis on silicon (low Z), tin (medium Z), and lead (high Z) plasmas. The velocities of the plasma have been extracted from CCD images obtained using a 250 ps gated ICCD Hamamatsu camera (C1764-03). This data has also been compared to ion velocity data, obtained from measurements made with two copper probes and an electrostatic energy analyser (ESA). EUV spectra, from 9.8 to 18 nm, were recorded on an absolutely calibrated JENOPTIK EUV Spectrograph, and these spectra provide additional information about the temperature of the plasma. The emission spectra have been analysed with the aid of the well known Cowan suite of atomic structure codes [2] [3] [4]. For a known plasma temperature the CR model predicts the ratios of the relevant ion stages within the plasma [5]. The combination of all of this information about the plasmas will provide insight into the differing behaviours of the low, medium and high-Z plasmas.

Experiment

The experiment uses a Nd:YAG laser at $1.064\ \mu m$. The beam is split in half with 440 ± 3 mJ per seed plasma with a spot size of $117 \pm 15\ \mu m$. The seed separation was 2.6 ± 0.5 cm. The spectrometer is oriented 45° to the target normal. The plasma imaging system is parallel to the target normal.

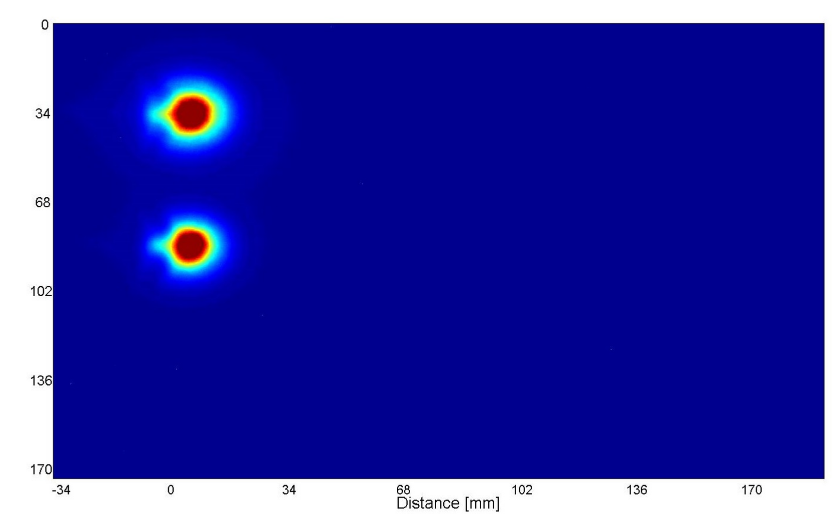


Figure 1: Silicon seed formation

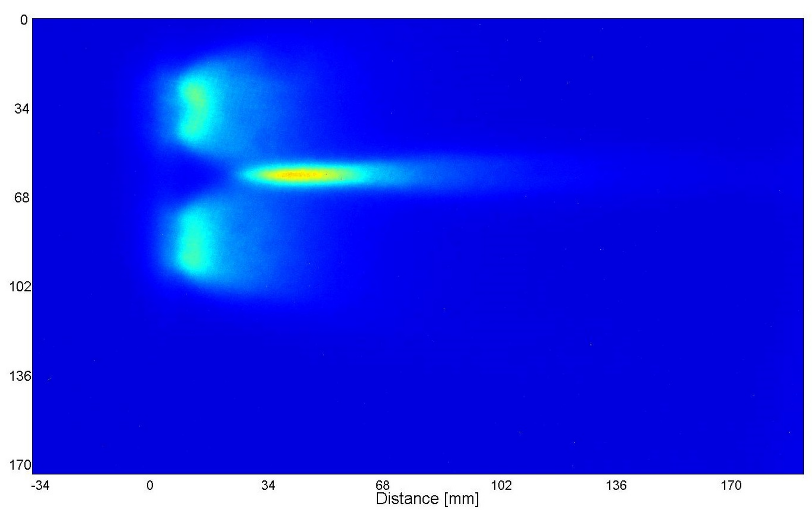


Figure 2: Silicon 200 ns after plasma formation

Collisional Radiative model

The CR model developed by Colombant and Tonon has been used to find the ratio of the n^{th} and $n+1^{th}$ ion stages which is governed by processes, two causing an electron to recombine with the ion (α_r, α_{3b}) and another is to further ionise the ion (S). The ratio is given by:

$$\frac{n_{z+1}}{n_z} = \frac{S(z,T_e)}{[\alpha_r(z+1,T_e)+n_e\alpha_{3b}(z+1,T_e)]}$$

Where:

- $S = \frac{9\times10^{-6}\zeta_z(T_e/\chi_z)^{1/2}}{\chi_z^{3/2}(4.88+T_e/\chi_z)}e^{(-\chi_z/T_e)}\ [cm^3s^{-1}]$
- $\alpha_r = 5.2\times10^{-14}(\chi_z/T_e)^{1/2}Z[0.429+\frac{1}{2}\log(\chi_z/T_e)+0.469(T_e/\chi_z)^{1/2}]\ [cm^3s^{-1}]$
- $\alpha_{3b} = 2.97\times10^{-27}\zeta_z/(T_e\chi_z^2(4.88+T_e/\chi_z))\ [s^{-1}]$
- $n_{ec} = \frac{4\pi^2c^2m_e\epsilon_0}{e^2}\frac{1}{\lambda^2}\ [cm^3]$

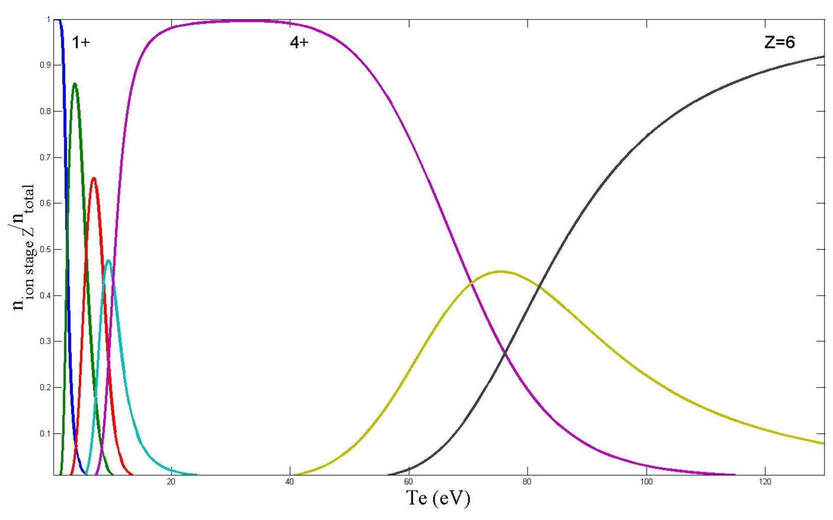


Figure 3: Carbon ionisation balance

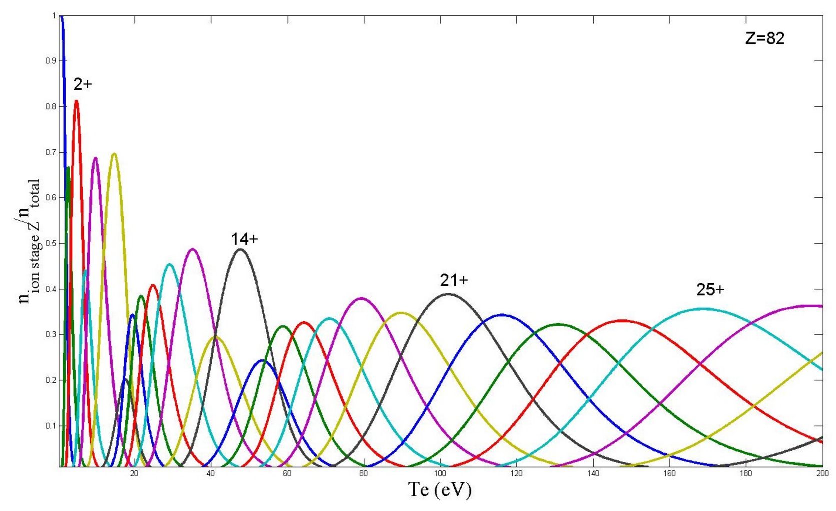


Figure 5: Lead ionisation balance

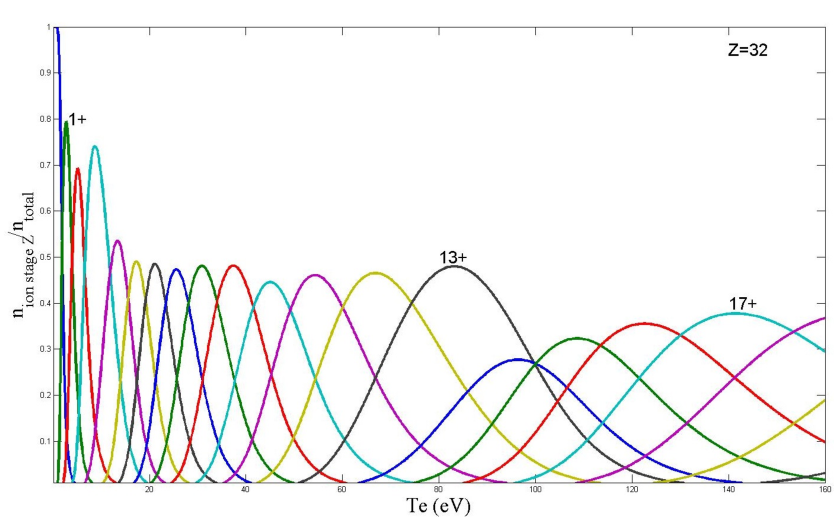


Figure 4: Germanium ionisation balance

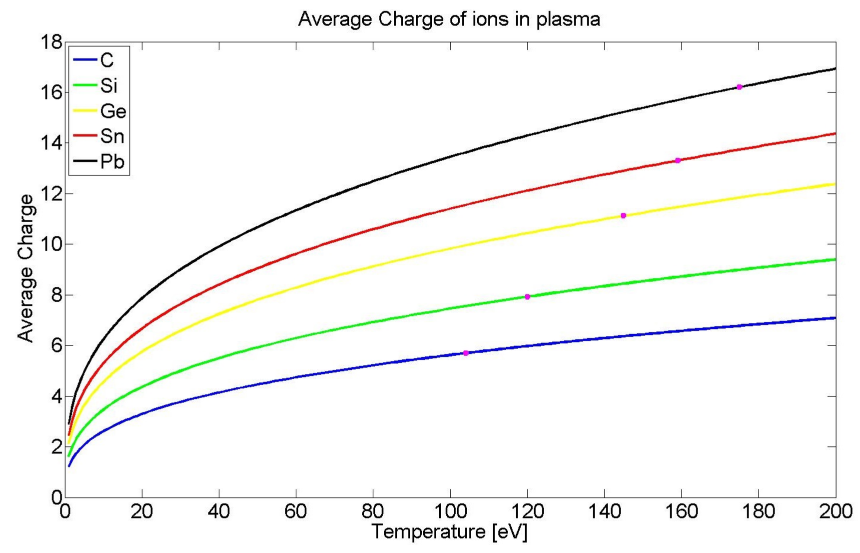


Figure 6: CR models prediction of average charge of ion in a plasma

Results

	Power Density $[W/cm^2]$	Temperature CR model $[eV]$	Temperature Spectra $[eV]$	Ion Velocity $[m/s]$ CR model $[m/s]$	Ion Velocity Camera $[m/s]$	Ion Velocity Probes $[m/s]$
C	$6.80 \pm 0.05 \times 10^{11}$	104 ± 2	78 ± 15	$4.09 \pm 0.02 \times 10^4$		
Si	$6.80 \pm 0.05 \times 10^{11}$	120 ± 2.5	123 ± 5	$2.91 \pm 0.01 \times 10^4$	$2.78 \pm 0.41 \times 10^4$	$2.85 \pm 0.25 \times 10^5$
Ge	$6.80 \pm 0.05 \times 10^{11}$	145 ± 3	100 ± 10	$1.96 \pm 0.05 \times 10^4$		
Sn	$6.80 \pm 0.05 \times 10^{11}$	159 ± 3.5	165 ± 4	$1.61 \pm 0.01 \times 10^4$	$1.08 \pm 0.41 \times 10^4$	$1.69 \pm 0.11 \times 10^4$
Pb	$6.80 \pm 0.05 \times 10^{11}$	175 ± 4	160 ± 10	$1.28 \pm 0.01 \times 10^4$	$1.86 \pm 0.41 \times 10^4$	

Emission spectra

The spectra of carbon and silicon were analysed with the aid of the NIST atomic database. Germanium was analysed using the Cowan suite of atomic structure codes coupled with the CR model as well as using known lines from *Bowen et al* [6]. Tin and lead were analysed using the Cowan suite of atomic structure codes [2] [3] [4].

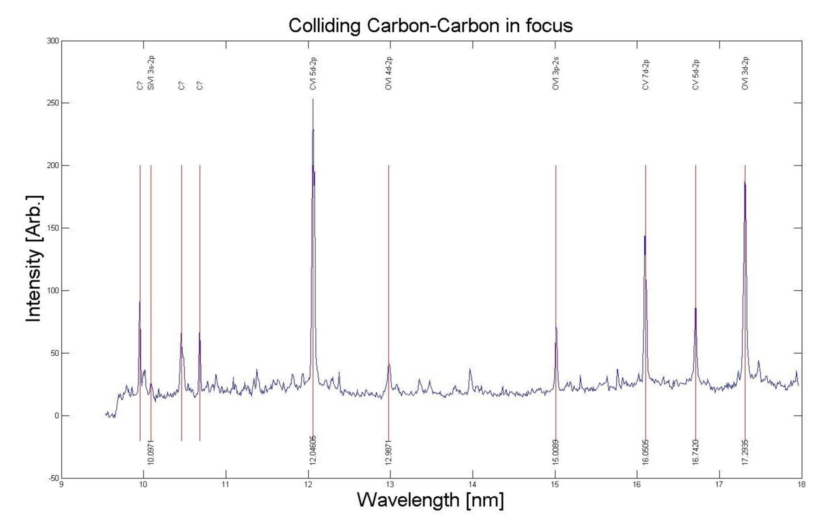


Figure 7: Carbon calibration

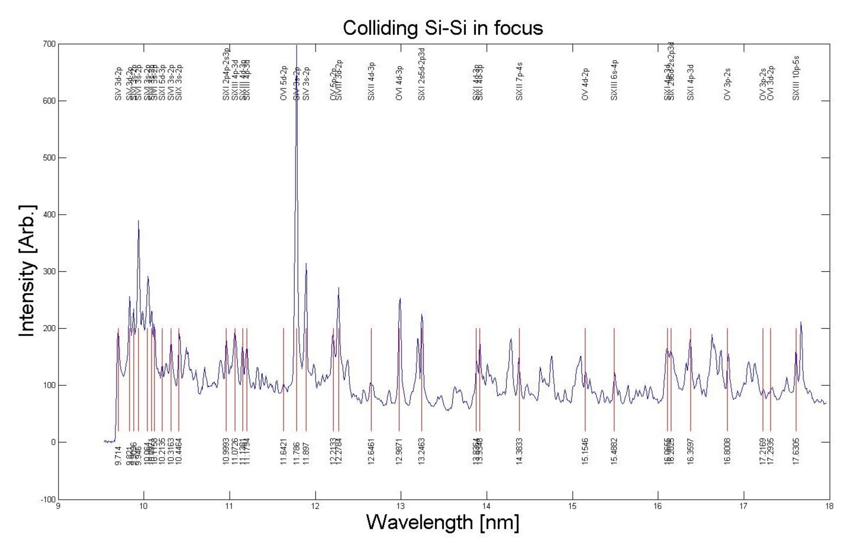


Figure 8: Silicon calibration

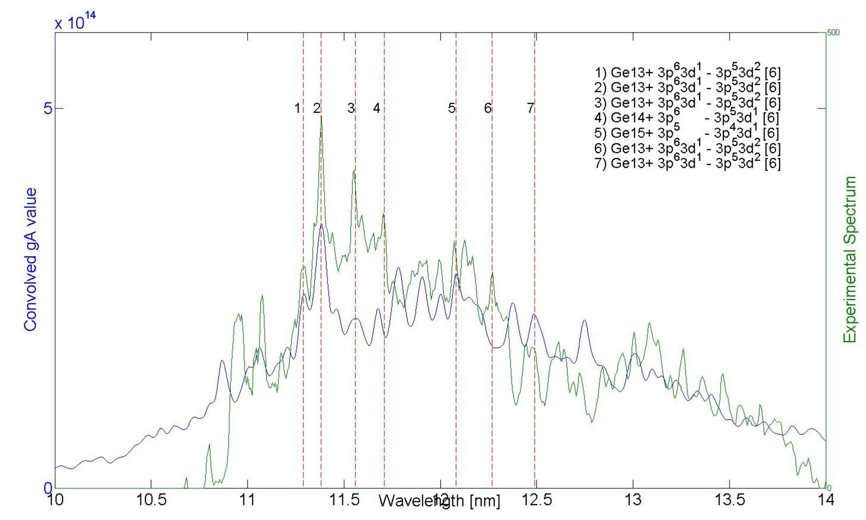
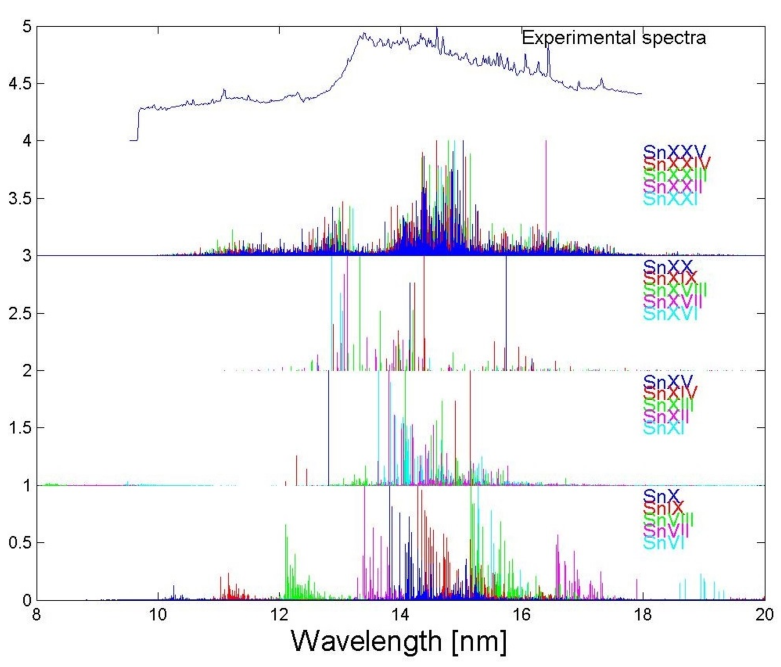


Figure 9: Germanium calibration



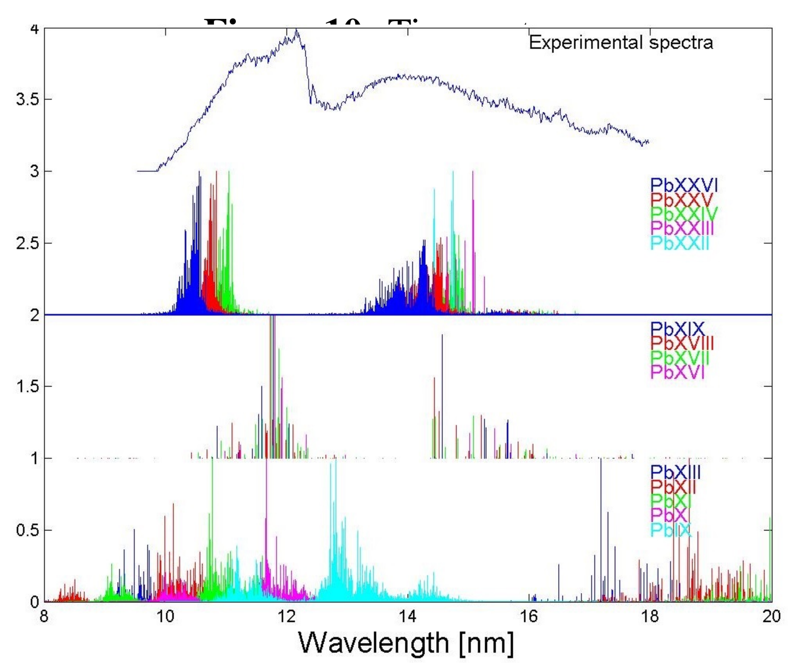


Figure 11: Lead spectra

Element	Transitions Considered
C:	*nd-2p,np-2s*
Si:	*nd-2p,ns-2p*
Ge:	*3d-3p*
Sn:	*nf-4d,5p-4d,4d-4p*
Pb:	*nf-5d,np-5d,5d-5p,5p-5s*

Conclusions

The temperatures extracted from the ion velocity measurements are broadly consistent with those determined from the spectra as well as with those calculated using the Colombant and Tonon formula. It is important to bear in mind that the outer lower density and lower temperature layer of the plasma affects the total EUV spectra due to the absorption of the EUV emission from the higher ionisation stages coupled to the emission from these lower ionisation stages.

Further Research

The identification of the remaining line emission that has not been identified. Absorption effects will be taken into account for the analysis of the emission lines as the cold lobes of the plasma are known to absorb and distort the purely emission spectra of a plasma.

References

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Acknowledgements

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